Durability Gap Analysis for Fiber-Reinforced Polymer Composites in Civil Infrastructure

by

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Abstract: The lack of a comprehensive, validated, and easily accessible data base for the durability of fiber-reinforced polymer (FRP) composites as related to civil infrastructure applications has been identified as a critical barrier to widespread acceptance of these materials by structural designers and civil engineers. This concern is emphasized since the structures of interest are primarily load bearing and are expected to remain in service over extended periods of time without significant inspection or maintenance. This paper presents a synopsis of a gap analysis study undertaken under the aegis of the Civil Engineering Research Foundation and the Federal Highway Administration to identify and prioritize critical gaps in durability data. The study focuses on the use of FRP in internal reinforcement, external strengthening, seismic retrofit, bridge decks, structural profiles, and panels. Environments of interest are moisture/solution, alkalinity, creep/relaxation, fatigue, fire, thermal effects (including freeze-thaw), and ultraviolet exposure.

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Introduction

Fiber-reinforced polymer (FRP) composites are increasingly being used in civil infrastructure in applications ranging from reinforcing rods and tendons, wraps for seismic retrofit of columns and externally bonded reinforcement for strengthening of walls, beams, and slabs, to all-composite bridge decks, and even hybrid (FRP composite in combination with conventional materials) and all-composite structural systems. Anecdotal evidence provides substantial reason to believe that, if appropriately designed and fabricated, FRP composite materials can provide longer lifetimes and lower maintenance than equivalent structures fabricated from conventional materials. However, actual data on durability is sparse, not well documented, and/or not easily accessible to the civil engineer. In addition, there is a wealth of contradictory data published in a variety of venues that confuses the practicing engineer.

The lack of a comprehensive database on FRP materials makes it difficult for the practicing civil engineer and designer to use FRP composites on a routine basis. Although a number of reviews have been published recently related to durability and test methods (Schutte 1994; Bank et al. 1995; Chin 1996; Liao et al. 1998) the focus of each has been to summarize the state of knowledge in general without emphasizing or attempting to prioritize critical areas in which needs are the greatest for collection, assimilation, and dissemination of data. This paper summarizes the results of such an effort in detailing critical gaps in knowledge vis-à-vis the durability of FRP composites to be used in civil infrastructure applications.

Scope and Background of Study

Based on a series of workshops, held under the aegis of the Civil Engineering Research Foundation (CERF) and the Market Development Alliance (MDA), with attendees from the user, owner, construction, design, materials, and manufacturing sectors, the use of FRP composites in the form of reinforcing bars (rebar), external reinforcement for strengthening on concrete structures, wraps, and jackets for the seismic retrofit of columns, piers and masonry walls, bridge decks and bridge systems, and wall panels and structural profiles, were identified as being of the maximum near-time market and application interest. Seven separate environmental conditions, moisture/solution, alkali, thermal (including temperature cycling and freeze-thaw), creep and relaxation, fatigue, ultraviolet, and fire, were then identified as being of primary importance vis-à-vis durability of FRP composites in the application areas already highlighted. Synergistic effects (i.e., effects resulting from the combination of multiple environmental

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Table 1. Subcommittee Structure and Membership

Subcommittee area	Membership
Moisture/ Solution	Dr. Donald Hunston (National Institute of Standards and Technology)—Chair Dr. Thomas Juska (Newport News) Prof. Vistasp Karbhari (University of California, San Diego) Prof. Roger Morgan (Texas A&M Univ.) Dr. Carol Williams (U.S. NSWC)
Alkaline environment	Prof. Brahim Benmokrane (Univ. of Sherbrooke)—Chair Dr. Salem Faza (Marshall Industries Composites) Prof. Hota GangaRao (West Virginia Univ.) Prof. Vistasp Karbhari (Univ. of California, San Diego) Prof. Max Porter (Iowa State Univ.)
Thermal effects	Dr. Thomas Juska (Newport News)–Chair Prof. Leif Carlsson (Florida Atlantic Univ.) Dr. Piyush Dutta (U.S. Army Cold Regions Research and Engineering Laboratory) Prof. Jack Weitzman (Univ. of Tennessee)
Creep/ Relaxation	Prof. Roger Morgan (Texas A&M Univ.)–Chair Dr. Colin Dunn (AMEES/Michigan State Univ.) Mr. Chris Edwards (Dow Chemical Co.)
Fatigue	Prof. Jack Lesko (Virginia Polytechnic Institute and State Univ.)–Chair Prof. Charles Bakis (Pennsylvania State Univ.) Dr. Clem Heil (Brandt Goldsworthy & Associates) Prof. Antonio Nanni (Univ. of Missouri-Rolla) Mr. Steven Phifer (Virginia Polytechnic Institute and State Univ.) Prof. Kenneth Reifsnider (Virginia Polytechnic Institute and State Univ.)
Ultraviolet exposure	Dr. Joannie Chin (National Institute of Standards and Technology)–Chair Dr. Jonathan Martin (National Institute of Standards and Technology) Dr. Tinh Nguyen (National Institute of Standards and Technology)
Fire	Dr. Usman Sorathia (NSWCCD)—Chair Dr. Richard Lyon (Federal Aviation Authority) Dr. Tom Ohlemiller (National Institute of Standards and Technology) Prof. Judy Riffle (Virginia Polytechnic Institute and State Univ.) Mr. Neil Schultz (VTEC)

Note: Chairs—Dr. Joannie Chin, National Institute of Standards and Technology; and Prof. Vistasp Karbhari, Univ. of California, San Diego. Coordinator—Mr. David Reynaud, Civil Engineering Research Foundation.

conditions, both in the absence and presence of load) are known to exacerbate individual effects, and these were considered as related to the dominant environmental condition.

Seven subcommittees were then assembled within the research panel, each of which focused on one of the above-mentioned environmental conditions. The overall structure of the panel and the membership of each of the subcommittees is listed in Table 1. Members were selected on the basis of their past research expertise in the specific areas.

Methodology Used in Gap Analysis

The primary objective of the gap analysis was to provide in easy to understand format, a synopsis of the current state of accessible knowledge of the effects of specific environmental conditions vis-à-vis the already identified high priority application areas, while providing a means of identifying and prioritizing areas of need. The analyses were intended to provide a snapshot of current knowledge. However, it must be emphasized that it is highly likely that sets of data, which were proprietary, confidential, or otherwise not easily accessible, were not considered in the analysis. This, however, is not viewed as a shortcoming since it emphasizes the lack of easily accessible data. In order to assist in the completion of the gap analysis each application area was evaluated by the team for the effects of individual environmental exposure conditions on the basis of two separate criteria (a) importance of data and (b) availability of data, the ranking of which would then be combined to provide an overall prioritization. The methodology for ranking used a scale of 1–5 as listed below. The use of the opposing scales for the two items ensures that when added, the highest priority would be for items that have a high level of importance/need and are not widely available. This would ensure that data for items that are either (a) not important or merely of academic interest and/or (b) already widely available, do not become priorities.

Ranking for Importance of Data

- 5: Critical, cannot go forward without it,
- 3: Important to have, and
- 1: Good to have, but not essential.

Ranking for Availability of Data

- 1: Widely available and validated,
- 3: Sparse and/or questionable, and
- 5: Not available.

In addition, effects on structural components and/or systems were considered in terms of effects on the composite itself (marked as A in the tables), effects on the interface (or adhesive between the concrete and the FRP composite) (marked as B in the tables), and effects on the substrate itself (marked as C in the tables).

Scope and Purview

It is critical that readers approach the summary presented in this paper, and the data provided in the actual report (CERF 2001), not as an indication of the susceptibility of FRP composites to environmental degradation, but rather as a road map both of validated data defining application-specific viability of materials systems, and of areas in which there is a paucity of well-documented data in a form easily accessible by the designer. It is the hope of the writers that the gap analysis will serve as a catalyst for renewed efforts to address areas wherein gaps have been identified both through (a) collection, validation, and dissemination of existing data, and (b) focused research to develop new pertinent data sets.

It should be noted that although the term durability is widely used, its meaning and implications are often ambiguous. In order to ensure that the term and its implications were completely understood for the purpose of the study, the durability of a material or structure was defined as *its ability to resist cracking, oxidation, chemical degradation, delamination, wear, and/or the effects of*

Table 2. Data Availability on Moisture/Solution Effects by Material System

Material system	Continuous immersion U	Continuous immersion 25%	Continuous immersion L	Humidity U	Humidity 25%	Humidity L	Cyclic effects U	Cyclic effects 25%	Cyclic effects L
C-PE	3	5	5	5	5	5	5	5	5
C-VE	5	5	5	5	5	5	5	5	5
C-E	3	3	5	3	5	5	5	5	5
G-PE	1	3	—[a]	3	5	3	5	5	—[a]
G-VE	1	5	—[a]	1	5	5	5	5	5
G-E	3	5	—[a]	3	5	3	3	5	5
A-PE	5	5	—[a]	5	5	3	5	5	—[a]
A-VE	5	5	—[a]	5	5	5	5	5	—[a]
A-E	1	5	—[a]	3	5	3	1	5	—[a]

Note: C: Carbon fiber, G: E-glass fiber, A: aramid fiber, PE: polyester resin, VE: vinylester resin, E: epoxy.

[a]Not recommended for use without testing.

foreign object damage for a specified period of time, under the appropriate load conditions, under specified environmental conditions.

Moisture/Solution Effects

Moisture diffuses into all organic polymers, leading to changes in thermophysical, mechanical, and chemical characteristics. The primary effect of the absorption is on the resin itself through hydrolysis, plasticization, saponification, and other mechanisms, which cause both reversible and irreversible changes in the polymer structure. In some cases, the moisture wicks along the fiber-matrix interphase and has been shown to cause deleterious effects to the fiber-matrix bond, resulting in a loss of integrity at that level. Moisture and chemicals have also been shown in the case of aramid and glass fibers to cause degradation at the fiber level. In the case of glass fibers, degradation is initiated by moisture-extracting ions from the fiber, thereby altering its structure. Aramid fibers absorb moisture, which can result in accelerated fibrillation under specific conditions. Solutions such as sodium hydroxide and hydrochloric acid are known to cause dramatic accelerated hydrolysis of Kevlar 49 yarn, especially in combination with temperature and stress. It is, however, possible to protect these fibers to a significant degree from rapid attack through the selection of appropriate resin systems, processing conditions, and the application of gel coats and protective coatings.

Since most FRP composites in civil infrastructure will come in contact with moisture and various solutions, either due to natural causes or location, or due to design or accident, it is essential that both the short- and long-term effects of these solutions are well understood and documented. The reader is referred to the excellent works by Marom and Broutman (1981), Apicella et al. (1983), Pritchard and Speake (1987), Weitsman (1998, 1991), Zheng and Morgan (1993), Schutte (1994), Sonawala and Spontak (1996), Karbhari and Zhang (2003), and Pritchard (1999), for further details and results.

Acknowledging that durability depends intrinsically on the constituents used in the material and that a variety of systems are now available, not all of which have equal amounts of historical data available even though the more recently developed systems may in fact have a greater resistance to degradation, Table 2 presents the perceived availability of data on the basis of the material system under consideration. In this table, effects are differentiated between unloaded specimens U, specimens under sustained loading at levels below 25% of ultimate, and specimens under sustained loading L. The overall synthesis of the results based on data importance, and availability is given in Table 3.

Based on the current state of knowledge, albeit incomplete, the following overall aspects are emphasized:

- In order to decrease the possibility of rapid movement of moisture and chemicals in solution into the bulk composite and towards the fiber surface, it is critical that an appropriate thickness of resin-rich surface exist in FRP composites used in this environment, with the resin layer remaining uncracked through the period of intended use,
- Acknowledging the impact of undercure on increase in moisture susceptibility of resins, cure kinetics of the resin and FRP composite need to be understood and materials need to be fully cured prior to use in the field,

Table 3. Overall Ranking of Gaps for Moisture/Solution Effects

Application area	Continuous exposure A[a]	Continuous exposure B[b]	Intermittent exposure A	Intermittent exposure B	Synergistic effects A	Synergistic effects B
Internal reinforcement						
Rebar	6	—	6	—	8	—
External reinforcement						
Beams	10	10	10	8	10	10
Slabs	10	10	10	10	10	10
Columns	10	10	10	10	10	10
Seismic retrofit						
Columns, piers	8	8	6	6	8	8
Walls	8	10	6	8	10	10
Deck systems						
Conventional beams/girders	10	8	6	6	10	8
Integral/composite beams/girders	10	10	6	8	10	10
Structural elements						
Wall panels, profiles	6	—	6	—	8	—

Note: A ranking of 1 indicates a low level of criticality, whereas a ranking of 10 represents a high level of criticality.

[a]A: Effects at the fiber-reinforced polymers composite level.

[b]B: Effects at the interface/bond/adhesive level.

Table 4. Overall Ranking of Gaps for Alkaline Exposure Effects

Application area	Under dry conditions and stress		Under wet conditions and no stress		Under set conditions and stress		Under wet conditions and stress and/or temperature	
	A[a]	B[b]	A	B	A	B	A	B
Internal reinforcement								
Rebar	8	8	6	6	10	10	10	10
External reinforcement								
Beams	8	8	6	6	10	10	10	10
Slabs	8	8	6	6	10	10	10	10
Columns	8	8	6	6	10	10	10	10
Seismic retrofit								
Columns, piers	8	8	6	6	10	10	10	10
Walls	8	8	6	6	10	10	10	10
Deck systems								
Conventional beams/girders	8	8	6	6	10	10	10	10
Integral/composite beams/girders	8	8	6	6	10	10	10	10
Structural elements								
Wall panels, profiles	8	8	6	6	10	10	10	10

Note: A ranking of 1 indicates a low level of criticality, whereas a ranking of 10 represents a high level of criticality.

[a]A: Effects at the fiber-reinforced polymers composite level.

[b]B: Effects at the interface/bond/adhesive level.

- Effects of solution ions/salts in conjunction with stress and temperature regimes need to be evaluated at the level of the fiber, interphase, matrix, and composite,
- It is emphasized that testing over short periods of time followed by extrapolation of results, especially for ambient temperature cure systems, can lead to erroneous results,
- Due to the effect of moisture on glass transition temperature, composites must be cured such that the T_g achieved is significantly higher than the maximum service temperature (a minimum level of 30°F above maximum service temperature is recommended for wet T_g), and
- Taking into account effects of degradation and damage tolerance requirements and the lack of sufficient data at present, the stress level in the composite should be limited under sustained factored loads at less than 25% of guaranteed design strength for glass fiber-reinforced polymers (GFRP), 30% for aramid fiber-reinforced polymers (AFRP), and 40% of guaranteed design strength for carbon fiber-reinforced polymers (CFRP).

Alkali Effects

Although FRP composites can come in contact with alkaline media through interaction with a variety of sources, including alkaline chemicals, soil (or solutions diffusing through soil), and concrete, the main concern at the present time stems from the potential effects of degradation due to concrete pore water solution, which is known to have a hydrogen ion concentration level as high as 13.5. A large body of research exists on the degradation of bare glass fibers in contact with (or in) alkaline solutions, especially those derived from concrete, and there is no doubt that bare glass fibers in this environment are severely degraded due to a combination of mechanisms ranging from pitting, hydroxylation, hydrolysis, and leaching. Although the presence of resins in FRP composites around individual filaments can be expected to protect the fibers from such attack, the alkaline solutions can accelerate the degradation of bond and of some resins themselves, especially if not fully cured. A good summary of mechanisms and effects can be found in Sen et al. (1993), Bank et al. (1995), Katsuki and Uomoto (1995), GangaRao and Vijay (1997), Porter and Barnes (1998), Chin et al. (1999, 2001), and Zhang and Karbhari (1999).

The results of the gap analysis based on the synthesis of data pertaining to the importance of data, and its availability in easily accessible, validated form, are presented in Table 4. Based on the current state of knowledge, albeit incomplete, the following overall aspects are highlighted:

- The use of mechanistic, and/or reliability based tools integrated with a risk-assessment methodology needs to be developed for life-prediction,
- Since the polymeric resin plays a critical role in protecting the fiber and slowing the diffusion process, preference should be given to the use of appropriate epoxies and vinylesters. The use of polyester resins is not recommended,
- In order to decrease the possibility of rapid movement of moisture and alkaline salts into the bulk composite, and towards the fiber surface, it is critical that an appropriate thickness of resin rich surface exist in FRP composites used in this environment, with the resin layer remaining uncracked through the period of intended use,
- Acknowledging the role of undercure on increase in moisture susceptibility of resins, it is recommended that the resin and FRP composite be fully cured prior to use in the field, and
- Taking into account effects of degradation and damage tolerance, the stress level in the FRP reinforcement should be limited under sustained factored loads to less than 30% of guaranteed design strength for GFRP and AFRP, and 40% of guaranteed design strength for CFRP.

Thermal Effects

Thermal effects considered in this section include response changes due to temperatures above the cure temperature, freezing and freeze-thaw conditions, and temperature variations and cycles. It is acknowledged at the outset that not all thermal exposure is deleterious since in a number of cases it can actually result in much needed postcure of FRP components. It is noted that

Table 5. Overall Ranking of Gaps for Thermal Exposure Effects

Application area	Elevated temperature conditions: Prolonged exposure at elevated temperature A[a]	B[b]	Thermal cycling A	B	Thermal gradients A	B	Freeze/freeze-thaw conditions: Prolonged exposure A	B	Thermal cycling A	B	Thermal gradients A	B
Internal reinforcement												
Rebar	6	6	6	6	6	6	2	6	2	6	6	10
External reinforcement												
Beams	6	6	6	6	6	6	2	6	2	6	6	10
Slabs	6	6	6	6	6	6	2	6	2	6	6	10
Columns	6	6	6	6	6	6	2	6	2	6	6	10
Seismic retrofit												
Columns, piers	6	6	6	6	6	6	2	4	2	4	4	8
Walls	6	6	6	6	6	6	2	6	2	6	6	10
Deck systems												
Conventional beams/girders	6	6	6	6	6	6	2	6	2	6	6	10
Integral girders	6	6	6	6	6	6	2	6	2	6	6	10
Structural elements												
Panels, profiles	6	6	6	6	6	6	2	6	2	6	6	10

Note: A ranking of 1 indicates a low level of criticality, whereas a ranking of 10 represents a high level of criticality.

[a]A: Effects at the fiber-reinforced polymers composite level.

[b]B: Effects at the interface/bond/adhesive level.

resins and adhesives soften over a temperature range, which causes an increase in viscoelastic response, a consequent reduction in elastic mechanical performance levels, and, in a number of cases, an increased susceptibility to moisture absorption. Prior research, materials testing, and anecdotal data has shown that in general:

- Subzero temperature exposure can result in matrix hardening, matrix microcracking, and fiber-matrix bond degradation,
- Freeze-thaw in the presence of salt can result in accelerated degradation due to the formation and expansion of salt deposits in addition to effects of moisture induced swelling and drying,
- Exposure to temperature above that of processing can result in an initial postcure followed by degradation due to thermal effects, and
- The coefficients of thermal expansion of adhesives can be orders of magnitude different from those of bulk resins and/or composites, and hence thermal gradients/exposure can cause premature debonding along the FRP composite-adhesive-concrete interfaces.

Results of infrastructure related testing and reviews of applications can be found in Lord and Dutta (1988), Dutta (1988), Gomez and Casto (1996), Karbhari and Engineer (1996), Green et al. (2000), and Miyano et al. (1999). The results of the gap analysis for both elevated temperature conditions and freeze/freeze-thaw conditions are shown in Table 5. Aspects that need to be emphasized include:

- The greatest concern with temperature effects on composite structures in civil engineering applications is that freeze/thaw conditions can potentially result in debonding of laminates,
- Failure is also possible if the laminating resin or adhesive softens excessively. The upper use temperature, the Material Operational Limit, of a given laminating resin defined as the temperature at which the flexural strength decreases to half the room temperature value, needs to be clearly followed for field implementation,
- FRP composites should not be used at temperatures above their glass transition temperatures, and for purposes of design it is recommended that materials be chosen that have a T_g at least 30° above the maximum expected use temperature,
- The synergistic effects of moisture/solution and thermal effects need to be considered further with investigations into both materials and structural systems response changes, and
- Long-term effects of differences in coefficients of thermal expansion and elastic properties of bonded materials need to be considered. Effects of the presence of large heat sinks as with concrete need to be assessed both for in-process and postprocess effects.

Creep/Relaxation

It has been well established that aramid and glass fibers have a higher level of susceptibility to creep rupture at lower stress levels than carbon fibers, with carbon fibers exhibiting little to no chemical-induced strength degradation, but having a larger spread in median failure times under stress rupture conditions as shown in Table 6 (Chiao and Moore 1971; Chiao et al. 1972; Moore et al. 1974). Qualifications for this data are that aramid and glass fibers (Bentur et al. 1985) are very susceptible to alkali-induced, chemical-induced

Table 6. Fiber Stress Rupture Level for 10% Population Failures After 75 Years Continuous Stress Exposure Under Ambient Conditions

Fiber type	10% Failure probability stress rupture level after 75 years (%)	Spread in median time to fail in decades
Carbon	75	6
Aramid	60	3
Glass	50	2.5

Table 7. Gap Analysis for Effects of Creep and Relaxation

Application area	Importance of data			Availability of data			Overall		
	A[a]	B[b]	C[c]	A	B	C	A	B	C
Internal reinforcement									
Rebar	5	—	—	3	—	—	8	—	—
External reinforcement									
Beams	5	5	3	3	3	3	8	8	6
Slabs	5	5	3	3	3	3	8	8	6
Columns	5	5	—	3	3	—	8	8	—
Seismic retrofit									
Columns, piers	3	3	—	3	3	—	6	6	—
Walls	3	3	—	3	3	—	6	6	—
Deck systems									
Conventional beams/girders	5	5	5	3	3	3	8	8	8
Integral girders	5	5	5	3	3	3	8	8	8
Structural elements									
Panels, profiles	3	3	—	3	3	—	6	6	—

Note: A ranking of 1 indicates a low level of criticality, whereas a ranking of 10 represents a high level of criticality.

[a]A: Effects at the fiber-reinforced polymers composite level.

[b]B: Effects at the interface/bond/adhesive level.

[c]C: Effects at the substrate level.

strength degradation, which, over long periods, will generally predominate over any fiber stress rupture attributes. Carbon fibers exhibit no chemical-induced strength degradation but exhibit a much larger spread in median failure times than aramid or glass fibers.

For any practical civil infrastructure composite, the creep-stress relaxation properties are dominated by the resin matrix dependent properties, rather than fiber or interfacial properties. Undercured resins are susceptible to significant creep and possible microcrack initiation during the early stages of service environment exposure. Absorbed moisture and higher service environment exposure temperatures both enhance creep susceptibility, which is ultimately diminished by enhanced further cure. There has been a study on ambient cured amine epoxies that shows the unreacted epoxy monomers can recrystallize in the undercured resin, causing a permanent brittle resin, unless such crystals are melted at 42.5°C (Morgan and O'Neal 1978). There has been one study of the long-term creep behavior of vinyl and polyesters as a function of cure conditions using flexural creep tests at ambient temperature (Bradley et al. 1998). Vinylesters that have been cured at room temperature had a greater creep exponent (n approximately 0.20) for power law creep (t^n) than vinylesters that were postcured to cross link completion at 93°C (n approximately 0.12). The total creep compliance as well as the time exponent n decreased systematically with increasing cure condition and time, with a creep compliance for room temperature cure for one day that is 250% more than that for a neat vinylester cured for four hours at 93°C.

In most cases, at the level of a structure or component, creep and stress relaxation can be guarded against or reduced significantly by taking advantage of the fact that creep and stress relaxation response is likely to be resin dominated for most practical civil infrastructure applications. Thus appropriate selection and processing of resins, and the designed placement of fibers can solve a large part of the challenge. Readers are referred to the excellent reviews by Liao et al. (1998) and Scott et al. (1995) for further explanations. The results of the gap analysis are shown in Table 7. Based on the current state of knowledge at the materials and structural levels the following aspects are highlighted:

- Significant testing and characterization needs to be conducted for material systems cured under ambient conditions taking into account the synergistic effects of moisture, stress levels, and temperature,
- Effects of shearing deformations which are often erroneously neglected need to be accounted for in the prediction of time-dependent behavior, and
- The use of standardized materials forms as in metals is highly recommended.

Fatigue

Fatigue, which is generally defined as the physical phenomenon that causes a material or component to fail after the application of an applied condition or conditions (cycles) even though the level of that condition is not high enough to cause failure on the first cycle of application, is an important consideration for the durability and safety of civil infrastructure. The loading may be mechanical (due to vehicle traffic, for example), thermal (from variations in temperature), or chemical (from seasonal road treatments, oxidation, NOX effects, water, etc.). Significant research is needed to develop a comprehensive understanding of the processes and mechanisms associated with fatigue failure in civil infrastructure components fabricated of FRP composites. Good reviews of the phenomena are given by Mandell (1982), Liao et al. (1998), and Konur and Matthews (1989), with the effect of environment; constituent materials and processes of fabrication being elucidated in Mandell et al. (1985), Branco et al. (1995), and McBagonluri et al. (2000). The results of the gap analysis are shown in Table 8 for various environmental conditions.

Data are currently available for a limited set of ''fatigue'' conditions, most notably constant amplitude fatigue at frequencies ranging from 1 to 10 Hz. Based on the work of Mandell (1982) and McBagonluri et al. (2000), the slope of the *S-N* curve for most planar glass/polymer composites can be expected to range from 10–12% ultimate tensile strength (UTS)/decade of life. There are existing life prediction methodologies such as developed by Reifsnider (1991) that can be used to combine processes,

Table 8. Overall Ranking of Gaps for Fatigue Effects

Application area	Sustained stress loading A[a]	B[b]	C[c]	Pure fatigue loading A	B	C	Fatigue and temperature A	B	C	Fatigue and moisture/salt A	B	C	Fatigue and creep A	B	C
Internal reinforcement															
Rebar	6	8	4	7	8	4	10	10	2	8	10	2	10	10	2
External reinforcement															
Beams	5	7	3	6	9	6	10	10	2	10	10	2	10	10	2
Slabs	5	7	3	5	9	6	10	10	2	10	10	2	10	10	2
Columns	7	9	4	7	9	4	10	10	2	10	10	2	10	10	2
Seismic retrofit															
Columns, piers	6	9	5	7	8	4	8	10	2	8	10	2	8	10	2
Shear walls	6	9	5	5	8	4	8	10	2	8	10	2	8	10	2
Deck systems															
Conventional beams/girders	6	9	1	9	9	1	10	10	2	10	10	2	10	10	2
Integral/composite beams/girders	6	9	1	6	9	1	10	10	2	10	10	2	10	10	2
Structural elements															
Wall panels, profiles	5	9	5	8	9	5	10	10	2	10	10	2	10	10	2

Note: A ranking of 1 indicates a low level of criticality, whereas a ranking of 10 represents a high level of criticality.

[a]A: Effects at the fiber-reinforced polymers composite level.

[b]B: Effects at the interface/bond/adhesive level.

[c]C: Effects at the substrate level.

their sequence, and severity to estimate life under known conditions. However, again there is a lack of understanding to accurately accelerate the individual and combined service conditions and environments to appropriately assess in a short period of time if a material system or structure will survive an extended service period.

Ultraviolet (UV) Radiation

Ultraviolet radiation that reaches the Earth's surface comprises about 6% of the total solar radiant flux and has wavelengths between 290 and 400 nm. Since most polymers have bond dissociation energies on the order of the 290 to 400 nm wavelengths in the ultraviolet region, they are greatly affected by exposure to this portion of the solar spectrum. The effects of ultraviolet (UV) exposure, or photodegradation, are usually confined to the top few microns of the surface. However, in some cases, degradation at the surface of a polymeric component has been shown to affect mechanical properties disproportionately, as flaws that result from surface photodegradation can serve as stress concentrators and initiate fracture at stress levels much lower than those for unexposed specimens. The effect of ultraviolet radiation is also compounded by the action of temperature, moisture, wind-borne abrasives, freeze-thaw, and other environmental components. A survey of the literature pertaining to outdoor exposure and accelerated laboratory tests of polymers indicates that a great deal of variability and uncertainty is associated with the current testing methodology. Furthermore, it is not always clear if changes in laminate mechanical properties can be attributed solely to UV effects or to a combination of UV and moisture. The overall ranking of gaps for UV effects is given in Table 9. The effects of UV exposure on composites can be reviewed in Roylance and Roylance (1976), Trabocco and Stander (1976), George et al. (1997), Lucki et al. (1981), Chin et al. (1997), Monney et al. (1998), and Liau and Tseng (1998).

A common practice in outdoor applications of FRP composites is to use a gel coat or other protective coating to shield the surface of the FRP from direct ultraviolet exposure. However, it must be noted that the use of a polymeric protective coating does not prevent UV-induced damage from occurring, but serves as a "self-sacrificing" layer to prevent the FRP surface being directly exposed to UV radiation. The protective coating itself will eventually be degraded by UV radiation and will need to be maintained. The most deleterious effects of UV exposure are probably not due to the actual UV damage, which is limited to the surface,

Table 9. Overall Ranking of Gaps for Ultraviolet Effects

Application area	Structural concerns A[a]	B[b]	C[c]	Aesthetic concerns A	B	C
Internal reinforcement						
Rebar	X[f]	X	X	X	X	X
External reinforcement						
Beams[d]	X	X	X	X	X	X
Slabs[d]	X	X	X	X	X	X
Columns	10	X	X	2	X	X
Seismic retrofit						
Columns, piers	10	X	X	2	X	X
Walls[e]	10	X	X	2	X	X
Deck systems						
Conventional beams/girders	8	X	X	2	X	X
Integral/composite beams/girders	8	X	X	2	X	X
Structural elements						
Wall panels, profiles[e]	10	X	X	2	X	X

Note: A ranking of 1 indicates a low level of criticality, whereas a ranking of 10 represents a high level of criticality.

[a]A: Effects at the fiber-reinforced polymers composite level.

[b]B: Effects at the interface/bond/adhesive level.

[c]C: Effects at the substrate level.

[d]Ultraviolet assumed not to be a factor on the nonexposed part.

[e]In exterior applications only.

[f]X: Not applicable.

Table 10. Overall Ranking of Gaps for Fire Effects

Application area	Flame spread			Fire endurance			Smoke and toxicity			Heat release		
	A[a]	B[b]	C[c]	A	B	C	A	B	C	A	B	C
Internal reinforcement												
Composite rebar	5	5	5	5	5	5	5	5	5	5	5	5
External reinforcement												
Beams/slabs/columns	8/10	8/8	—	10/10	10/10	6/6	6/10	6/8	—	8/10	8/8	—
Seismic retrofit												
Columns/piers/walls	8/10	8/8	—	10/10	10/10	6/6	6/10	6/8	—	8/10	8/8	—
Deck systems												
Conventional beams/girders	6/8	4/4	—	8/8	6/6	4/4	4/8	4/6	—	6/8	6/6	—
Integral/composite beams/girders	8/10	8/8	—	10/10	10/10	—	6/10	6/8	—	6/10	6/10	4/4
Structural elements												
Wall panels, profiles	6/8	6/8	—	8/8	8/8	—	4/8	4/6	—	4/8	4/8	—

Note: The rating is provided in the format—open/confined.

[a]A: Effects at the fiber-reinforced polymers composite level.

[b]B: Effects at the interface/bond/adhesive level.

[c]C: Effects at the substrate level.

but to the potential for increased moisture ingress in the damaged regions. It is recommended that future research in UV radiation effects on composites be conducted in the following areas:

- Development of polymeric matrix resins that have inherent stability to UV radiation, which would allow for the elimination of the protective coating,
- During UV exposure, specimens should be subjected to mechanical loads similar to the type that they will encounter in service, and
- New UV testing methodologies based on reliability theory and the idea of effective dosage, already being implemented in the polymer coatings field, should be extended to FRP materials.

Fire

A significant concern in any application of organic matrix-based composites is the possibility that an accidental (or deliberate) fire may ignite the composite material. This may result in the spread of flame on the composite surface, and may also release heat and generate potentially toxic smoke. The fibers displace polymer resin, making less fuel available to the fire. When the outermost layers of a composite lose their resin due to heat-induced gasification, they act as an insulating layer, slowing heat penetration and evolution of gases from the depth of the composite. It was recognized that fire-related issues associated with composite materials are more severe in confined spaces (such as tunnels and buildings) as opposed to open spaces (such as roads and bridges). As such, the gap analysis was conducted on two bases: (1) fires in open spaces and (2) fires in confined spaces. The effect of fire is initially exhibited by the heating up of the composite surface. Over the depth of composite material heated up to temperatures past the glass transition temperature, the composite exhibits a corresponding loss of modulus. Below the temperature of chemical degradation, this loss in modulus is reversible. Further increase in temperature, such as above 450°F for glass/vinylester, results in the degradation of the chemical structure of the resin. This thermal damage results in irreversible loss in load bearing characteristics. The overall ranking of gaps for fire effects is given in Table 10. A representative set of data, as an overview, can be gleaned from Sorathia et al. (1997), Sorathia et al. (1993), Milke and Vizzini (1993), Ohlemiller and Cleary (1999), Scudamore (1994), Dao and Asaro (1999), and Ohlemiller and Shields (1999).

Summary and Recommendations

Based on the gap analysis conducted for each of the selected environmental conditions, it appears that there is a substantial commonality of needs, which provides for the selection of a set of data/research requirements that is critical to the generic implementation of FRP composites in civil infrastructure. These needs, in no particular order of priority (since it is difficult to transition or compare the level of need within one category of environment to that in another), are as follows:

- Collection, assessment, and appropriate documentation of available data in a form useable by the civil engineer/designer,
- Testing over extended (18+ months) time periods. Tests conducted over short time periods (less than 18 months) can yield misleading results due to effects of postcure and slow interphase and fiber level degradation, and can provide an erroneous level of comfort in some cases,
- Testing under combined conditions (stress, moisture, solution, temperature, and/or other regimes) at both the materials and structural levels is critical,
- Assessment and characterization of the effects of incomplete cure and undercure, especially for ambient temperature cure systems, are essential,
- Development of standardized solutions and conditions for laboratory studies that closely simulate actual field conditions, and
- Development of appropriate resin systems, gel coats, and coatings that would serve as protective layers for the bulk composite against external influences including environmental conditions, intended, and accidental damage.

Based on the results of the gap analysis conducted through the present study, and on the overall results of the investigation (through review of literature, discussions with experts in the area of durability, results of discussions of the user and supplier panels, and subsequent discussions with members of the FRP composites and civil engineering industries) a three-pronged approach is recommended for future activities in continuation of this study as described in the following.

Integrated Knowledge System

Acknowledging the current difficulty in accessing data, and the possible loss of valuable data generated in the past through isolated studies, it is recommended that an integrated knowledge system be established at the earliest possible opportunity. This knowledge system would serve as a repository for data on durability that would be pertinent to civil engineering applications and in a form that is of use and easy to access by civil engineers, contractors, and designers. The knowledge system would contain a number of sets of data sets, which could either be used as single sets of reference, or in an integrated manner to aid design.

Establishment of Methodology

The current gap-analysis exercise has provided a list of data needs related to specific application areas and environmental conditions. It is hoped that the results of this study will spur efforts to fill in areas identified as being high priority based on the importance and current availability of data. In order to ensure that efforts aimed at filling in gaps are not conducted in isolation and that appropriate protocols are used, it is recommended that appropriate protocols be established for testing, data collection, and validation. These protocols would provide a basis for generation and collection of future data cognizant with the eventual requirements of a structural design methodology.

Implementation of Plans for Field Assessment

It is well established that durability data generated through laboratory experiments can differ substantially from field data. The determination of actual durability under field conditions over extended periods of time is essential for the optimal design of FRP composites for use in civil infrastructure. It is thus critical that steps be taken to collect, on an ongoing basis, data from field implementations. This data is invaluable to the establishment of appropriate durability based design factors, and the opportunity of having new projects from which such data could be derived in a scientific manner should not be wasted.

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